

Astroparticle Physics: Puzzles and Discoveries

V. Berezhinsky

INFN, Laboratori Nazionali del Gran Sasso, Assergi (AQ) 67010 Italy
and Institute for Nuclear Research, Moscow

Abstract. Puzzles often give birth to the great discoveries, the false discoveries sometimes stimulate the exiting ideas in theoretical physics. The historical examples of both are described in Introduction and in section “Cosmological Puzzles”. From existing puzzles most attention is given to Ultra High Energy Cosmic Ray (UHECR) puzzle and to cosmological constant problem. The 40-years old UHECR problem consisted in absence of the sharp steepening in spectrum of extragalactic cosmic rays caused by interaction with CMB radiation. This steepening is known as Greisen-Zatsepin-Kuzmin (GZK) cutoff. It is demonstrated here that the features of interaction of cosmic ray protons with CMB are seen now in the spectrum in the form of the dip and beginning of the GZK cutoff. The most serious cosmological problem is caused by large vacuum energy of the known elementary-particle fields which exceeds at least by 45 orders of magnitude the cosmological vacuum energy. The various ideas put forward to solve this problem during last 40 years, have weaknesses and cannot be accepted as the final solution of this puzzle. The anthropic approach is discussed.

1. Introduction

ALL GREAT DISCOVERIES IN ASTROPHYSICS
APPEARED UNPREDICTABLY AS PUZZLES.
WHAT WAS PREDICTED WAS NOT FOUND.

Not many good things fall down on us from the sky, but discoveries do. They arrive as the puzzles, and usually disappear as the errors. But sometimes they become real, leaving behind the great discoveries. I will give below a short list of astrophysical discoveries of the last four decades, separating intuitively astrophysics from cosmology.

Quasars were discovered in early 1960s as compact radio sources. G. Mathews and A. Sandage in 1960 identified radio source 3C48 with a stellar-like object. M. Schmidt in 1963 deciphered the optical spectrum of quasar 3C273 assuming its redshift, $z = 0.158$. Surmounting resistance of sceptics, this explanation moved the source to the distance of 630 Mpc and made its luminosity uncomfortably large, $L \sim 10^{46}$ erg/s. It was a puzzle, and many respectable astrophysicists spent years trying to squeeze the source back into Galaxy. All of them failed, and in the end the puzzling energy release resulted in the discovery of a *black hole*, an object of general relativity.

Pulsars were discovered first in 1967 by a student of A. Hewish, Jocelyn Bell. She observed a puzzling periodicity of radio-pulses from an unknown source. After short but intense discussion of different possible sources, including extraterrestrial civilizations and “little green men”, the magnetized rotating neutron stars, the pulsars, were found to be responsible. It opened a new

field of cosmic physics: *relativistic electrodynamics*.

The atmospheric neutrino anomaly and the solar neutrino problem went along most difficult road to the status of discovery. The puzzling phenomenon in both cases was a neutrino deficit as compared with calculations. The solar neutrino experiments have been started by Ray Davis in 1960 in Brookhaven. With time the solar-neutrino deficit raised, but scepticism of the community raised too. Pushed first by Ray Davis and John Bahcall, the solar neutrino problem moved like a slow coach along a road of three decades long. Fortunately, physics differs from democracy: opinion of majority means usually less than that of ONE. In the end the two obscure puzzles (solar and atmospheric neutrino deficits) have turned into discovery of the most fascinating phenomenon, *neutrino oscillations*, theoretically predicted by Bruno Pontecorvo.

Supernova SN 1987a became an elementary-particle laboratory in the sky for a study of properties of neutrinos, axions, majorons *etc.* Detection of neutrinos became a triumph of the theory: the number of detected neutrinos, duration of the neutrino pulse and estimated neutrino luminosity have appeared in agreement with theoretical prediction. Gravitational collapse as a phenomenon providing the SN explosion has been established ... and a puzzle appeared. It was the triumph of the incomplete theory, without rotation of collapsing star. The asymmetric ring around SN 1987a implies that the presupernova was a rotating star (it would be a surprise if not!). Rotation should diminish the neutrino luminosity or even change the collapsing scenario. Why then there is a beautiful agreement between theory and observation? This problem still expects its solution.

1.1. Greatness of false discoveries

WHEN FIRST APPEARED THE PUZZLES LOOK WEAK.

SAVE YOUR TIME SAYING: IT'S RUBBISH.

IN 90% OF CASES YOU WILL BE RIGHT,
BUT YOU MAY MISS THE GREAT PHYSICS.

False discoveries often have great impact on physics, and *Cyg X-3* is a famous example.

Cyg X-3 is a galactic binary system well studied in all types of radiations, most notably in X-rays. In 80s many EAS arrays detected from it the 4.8 hour periodic "gamma-ray" signal in VHE (Very High Energy, $E \geq 1$ TeV) and UHE (Ultra High Energy, $E \geq 0.1 - 1$ PeV) ranges. The list of these arrays included Kiel, Haverah Park, Fly's Eye, Akeno, Carpet-Baksan, Tien-Shan, Plateau Rosa, Durham, Ooty, Ohya, Gulmarg, Crimea, Dugway, Whipple and others. Probably it is easy to say that there was no single EAS array which claimed no-signal observation. Additionally, some underground detectors (NUSEX, Soudan, MUTRON) marginally observed high energy muon signal from the direction of this source. Apart from the Kiel array, which claimed 6σ signal, the confidence level of detection was not high: $3 - 4\sigma$.

In 1990 - 1991 two new-generation detectors, CASA-MIA and CYGNUS, put the stringent upper limit to the signal from *Cyg X-3*, which excluded early observations.

Apart from two lessons:

- (i) good detectors are better than bad ones,
 - (ii) " 3σ " discoveries should not be trusted, even if many detectors confirm them,
- experience of *Cyg X-3* has taught us how to evaluate statistical significance searching for periodic signals.

The false discovery of high energy radiation from *Cyg X-3* had great impact on theoretical high energy astrophysics, stimulating study of acceleration in binary systems, production of high energy gamma and neutrino radiation and creation of high energy astrophysics with new particles, such as light neutralinos, gluinos *etc.*

2. Ultra High Energy Cosmic Ray (UHECR) Puzzle

This is the oldest puzzle in physics which exists for 40 years, and most probably now is close to being resolved. It appeared in 1966 together with prediction of the Greisen-Zatsepin-Kuzmin (GZK) cutoff [1]. As physical phenomenon the GZK cutoff is explained by production of pions by UHE extragalactic protons interacting with CMB photons. The energy of CMB photon in the Lorentz system, where proton is at rest is Γ times larger than in the laboratory system (where Γ is Lorentz factor of a proton) and when this energy exceeds the mass of pion, the proton energy loss becomes large, and the spectrum of UHE protons obtains steepening which is (incorrectly but impressively!) called the “GZK cutoff”. For the diffuse spectrum the GZK feature (steepening) starts at energy $(3 - 5) \times 10^{19}$ eV. The UHECR puzzle was born simultaneously with

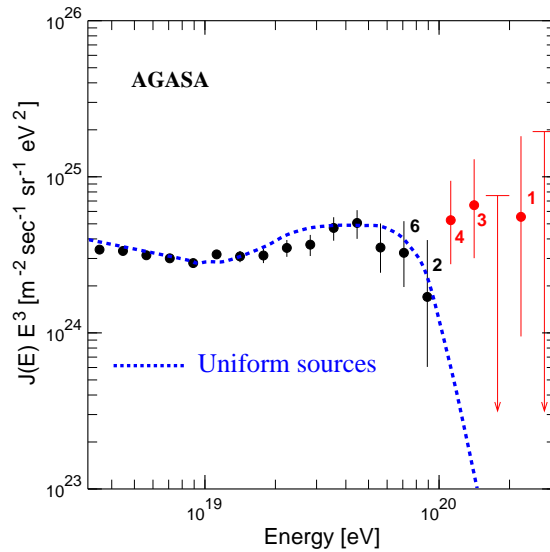


Figure 1. UHECR spectrum measured by AGASA detector in 1990 -1996 in comparison with calculated diffuse spectrum. The excess of events over predicted GZK cutoff is clearly seen. At present “AGASA excess” includes 11 events at energy $E \geq 1 \times 10^{20}$ eV.

the prediction of the GZK feature: already in 1966 there were known at least three events with energies above the GZK cutoff. With time the number of these particles increased and in 1994 the famous golden Fly’s Eye event [2] with energy $\sim 3 \times 10^{20}$ eV was detected. The energy of this event was determined very reliably and with the high precision. It questioned the presence of the GZK cutoff. However, most serious arguments against presence of the GZK feature were given by AGASA data [3]. In Fig. 1 the excess of AGASA events over predicted GZK cutoff is shown for data of 1996 - 1998 with 8 detected particles at energy $E \gtrsim 1 \times 10^{20}$ eV, in 2004 this number reaches reached 11 (for a review of observational data see [4]). The GZK cutoff is predicted for extragalactic protons, but already in 70s it was known that other conservative UHE signal carriers, UHE nuclei, suffer the steepening of the spectrum approximately at the same energy as protons [5, 6]. The other reasonable carriers, UHE photons, have too small absorption length interacting with radio-photons (see [7]).

2.1. New-physics solutions

No viable astrophysical solution to the “AGASA excess” was found, and the solutions with “new physics” have been proposed. I will give here the short list of the new solutions without

references which can be found in [8]

- *Superheavy Dark Matter.* Long-lived Superheavy Dark Matter Particles are accumulated in galactic halos. These particles are naturally produced gravitationally at post-inflationary epoch and at mass $m_x \sim 10^{13}$ GeV they provide CDM density as observed by WMAP. These particles can be long-lived, with lifetime exceeding the age of the Universe. Decays of these particles produce UHECR without GZK cutoff (most of UHE particles come from Galactic halo).
- *Topological Defects (TD).* There are various mechanisms of production of UHE particles by TD. In some cases TD become unstable and decompose to constituent fields (superheavy Higgs and gauge bosons), which then decay to ordinary particles. This mechanism works for cusps and superconducting cosmic strings. In case of monopoles and antimonopoles connected by strings, high energy particles are produced at annihilation of monopole-antimonopole pairs. The most promising candidates are necklaces and monopole-antimonopole pairs connected by string. UHECR from TD have a spectrum with a soft GZK cutoff which does not contradict observations.
- *Resonant neutrinos.* Very high energy neutrinos are resonantly absorbed by target neutrinos comprising Hot Dark Matter (HDM): $\nu + \bar{\nu}_{HDM} \rightarrow Z^0 \rightarrow \text{hadrons}$. Very large flux of primary neutrinos with superhigh energies is needed for this hypothesis.
- *Light gluino.* Light gluinos can be effectively produced by TD or in pp-collisions in astrophysical sources. They weakly degrade in energy interacting with microwave radiation. The interaction of UHE light gluino with nucleons is similar to that of UHE proton. Light gluino is disfavored by accelerator experiments.
- *Strongly interacting neutrino.* In extra-dimension theories, for example, neutrino can have large cross-section of scattering off the nucleon. In this case neutrino can be a carrier of UHE signal from remote astrophysical sources.
- *Lorentz invariance breaking.* In this case for protons with energies 10^{20} eV and higher, the c.m. energy could be not enough for production of pions in collisions with microwave photons.

It is interesting that these new ideas, in particular, Superheavy Dark Matter and Lorentz-invariance violation, first proposed in 1972 [9] to solve UHECR puzzle, are developed now independently of UHECR.

2.2. Towards astrophysical solution

GZK cutoff is nothing but a signature of UHE proton interaction with CMB.

Are there some other signatures of the same interaction, and what they tell us about UHECR problem?

Such signature is known since long time [10]: this is the *dip*; the tiny feature in the proton spectrum left behind by production of electron-positron pairs in collisions with CMB photons ($p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^-$). This feature is seen better when analyzed in terms of the modification factor

$$\eta(E) = J_p(E)/J_p^{\text{unm}}(E), \quad (1)$$

where $J_p(E)$ is proton spectrum calculated with all energy losses included and $J_p^{\text{unm}}(E)$ is one calculated with adiabatic energy losses (red-shift) only. The advantage of modification factor is its model-independence [11, 12, 13], in contrast to GZK cutoff which at $E \geq 1 \times 10^{20}$ eV is strongly model dependent.

The calculated modification factor is shown in comparison with experimental data in Fig. 2. As Fig. 2 shows the pair production dip and beginning of GZK cutoff up to energy 1×10^{20} eV is reliably confirmed by all experimental data including AGASA. As to AGASA excess at

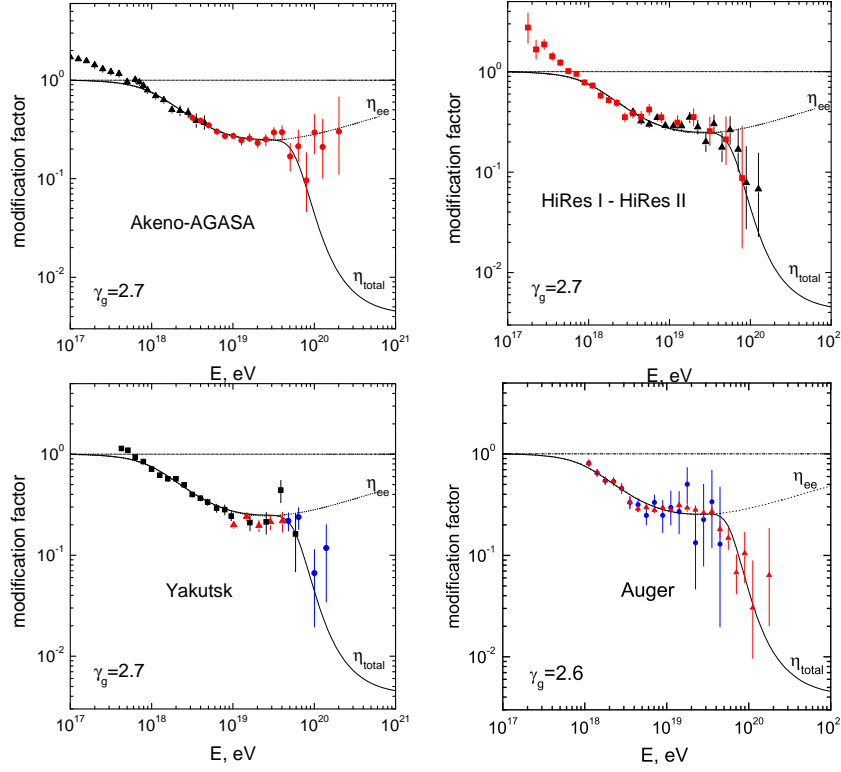


Figure 2. The predicted pair-production dip in comparison with Akeno-AGASA, HiRes, Yakutsk and Auger data. The first three experiments confirm dip with good $\chi^2/\text{d.o.f.} \approx 1.0-1.2$, while the Auger data are characterized by larger $\chi^2/\text{d.o.f.}$ (see the text). The data of Fly’s Eye (not presented here) confirm the dip as well as AGASA, HiRes and Yakutsk.

$E > 1 \times 10^{20}$ eV it can be explained by some other reasons, e.g. [14] by systematic energy errors combined with statistical fluctuations. The large χ^2 in comparison of the dip with Auger data is explained by energy errors not included in the analysis.

2.3. Evidence for GZK cutoff

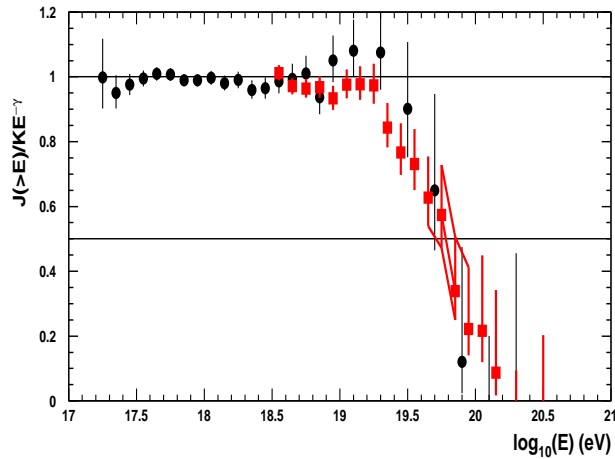


Figure 3. $E_{1/2}$ as numerical characteristic of GZK cutoff in the integral spectrum (see text).

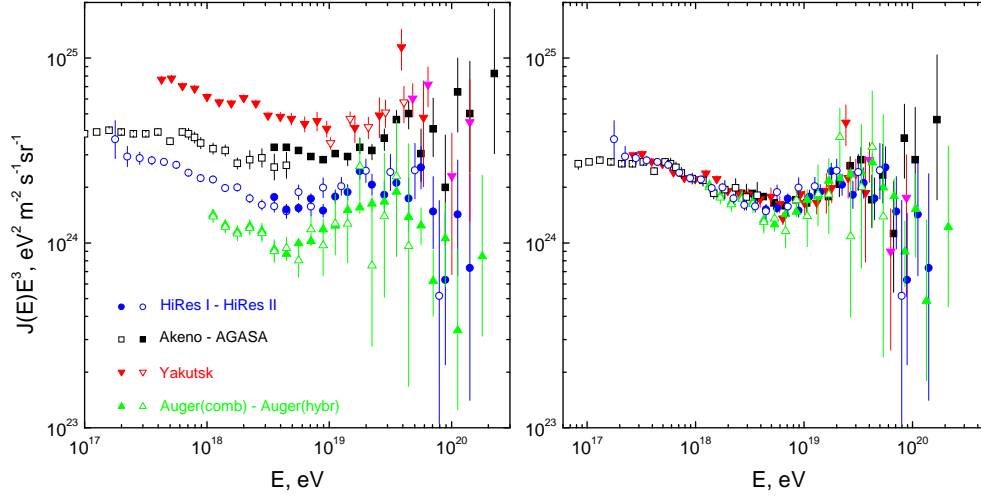


Figure 4. The spectra and fluxes measured by Yakutsk, AGASA, HiRes and Auger before (left panel) and after (right panel) energy calibration.

The Fig. 2 shows that data of HiRes, Auger and Yakutsk are consistent with GZK cutoff. The presence of GZK cutoff is seen most clearly in the HiRes data. However, low statistics and a possibility of imitation of the observed steepening by other reasons, e.g. by “acceleration cutoff”, precludes one from making the final conclusion. Recently, HiRes collaboration obtained the numerical confirmation that this steepening is really the GZK cutoff [15]. In the integral spectrum the GZK cutoff is characterized by energy $E_{1/2}$, where calculated spectrum $J(> E)$ becomes half of power-law extrapolation spectrum $KE^{-\gamma}$ from low energies. As calculations [10] show this energy is $E_{1/2} = 10^{19.72}$ eV for a wide range of generation indices from 2.1 to 2.8. HiRes collaboration found $E_{1/2} = 10^{19.73 \pm 0.97}$ eV in a good agreement with the theoretical prediction. In Fig. 3 we reproduce the HiRes graph from which $E_{1/2}$ was determined. The plotted value is given by ratio of measured flux $J(> E)$ and its power-law approximation $KE^{-\gamma}$. Extrapolation of this ratio to the higher energies is given by 1, while intersection of measured ratio with horizontal line 1/2 gives $E_{1/2}$.

2.4. Calibration of detectors with help of dip and GZK cutoff

The fluxes measured by Yakutsk, AGASA, HiRes and Auger are displayed in Fig. 4 (left panel). To the large extent the great discrepancy seen there is caused by comparison of the values $E^3 J(E)$ and thus systematic energy errors affect strongly this contradiction. As was demonstrated in [16, 12, 13] the energy calibration with help of the dip results in good agreement between the absolute fluxes of all detectors. Here we use the different approach for calibration of the detectors, based on both features, dip and GZK cutoff. Since energies as measured by HiRes fit well the both features and especially GZK numerical characteristic $E_{1/2}$, we assume that HiRes energies are correct and the energies of all other detectors must be shifted by factor λ to reach the best agreement in fluxes (see also [17]). This procedure gives values of λ equal to 1.2, 0.75, 0.83, and 0.625 for Auger, AGASA, Akeno and Yakutsk, respectively. This calibration does not give minimum χ^2 for the dip shape, but describes better the dip and beginning of GZK cutoff together. The fluxes after this energy calibration are shown in Fig. 4 (right panel).

2.5. Conclusions

The dip and beginning of the GZK cutoff at $E \leq 1 \times 10^{20}$ eV are signatures of proton interaction with CMB. They are confirmed with good accuracy by all experimental data, including AGASA. The GZK cutoff is seen most clearly in HiRes data and does not contradict Auger and Yakutsk data. HiRes experiment has numerical proof in the form of value $E_{1/2}$ that observed steepening is really GZK cutoff. AGASA excess can be explained by systematic energy errors combined with insufficient statistics. The UHECR fluxes and spectra measured by all four detectors coincide well after energy calibration of detectors with help of dip and GZK cutoff. As recent Auger data [18] indicate, the sources of UHECR can be AGN (see [19] for analysis).

3. Cosmological Puzzles in the Past and Present

The theoretical basis of cosmology is given by Friedmann solution of the Einstein equation. After discovery of highly isotropic CMB radiation and observational indications to the flat universe, it was understood that Friedmann solution leads to two puzzles: *horizon* and *flatness* problems.

The *horizon problem* can be explained in following way.

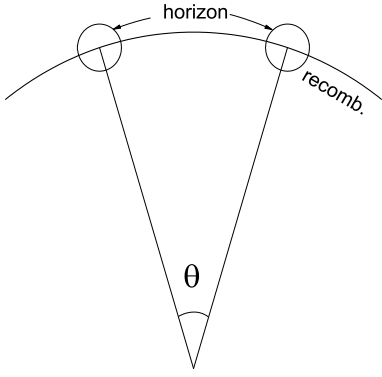


Figure 5. Two regions on recombination sphere ($z = z_{\text{rec}}$ separated by the horizon distance ct_{rec} .)

CMB radiation decouples from matter after recombination time at red-shift $z \approx 1100$ or $t_{\text{rec}} \approx 1.2 \times 10^{13}$ s. Two regions separated by horizon length ct_{rec} (see Fig. 5) are seen at angle $\theta \approx (1 + z_{\text{rec}})ct_{\text{rec}}/ct_0$, where $t_0 \approx 13.7$ Gyr is the age of the universe. These regions are causally disconnected and therefore the regions in the sky separated by angle $\theta \gtrsim 2^\circ$ cannot have equal CMB temperature. This conclusion is in contradiction with observed isotropy of CMB radiation.

Why the universe is *flat* now?

Within Friedmann solution it can be only due to initial conditions at $t_{\text{Pl}} \sim 1/m_{\text{Pl}}$. To have $\Omega - 1 \sim O(1)$ now, it is necessary to have at $t \sim t_{\text{Pl}}$ $\Omega - 1 \sim \xi$ with $\xi \sim 10^{-30}$.

If $\Omega - 1 \gg |\xi|$ the universe collapses during time much shorter than the age of universe now. If $\Omega - 1 \ll -|\xi|$ galaxies and stars do not have enough time to be formed. Such fine-tuning is highly unnatural.

The third cosmological puzzle was observation of rotational curves in galaxies and cluster of galaxies, which showed that virial (gravitational) masses of the objects are much bigger than visible (luminous) mass. It was interpreted as dominance of weakly interacting Dark Matter (DM). At present there are many particle candidates for DM with detailed description how these particles can be dominant in universe and produce Large Scale Structures (LSS).

As it is well known the first two puzzles were solved assuming an early stage in expanding universe different from Friedmann regime: *inflation*. At the different level of physical realization, this stage was proposed in works by E. Gliner (1965) [20], A. Starobinsky (1979) [21], K. Sato (1981) [22], A. Guth (1981) [23], A. Linde (1983) [24], A. Albrecht and P. Steinhardt (1982) [25], and spectrum of density perturbations (“galaxy formation”) imposed by this stage, was first studied by S. Mukhanov and G. Chibisov [26].

Inflation is also expanding solution of the Einstein equation, but driven by potential of the scalar field ϕ , inflaton. Expansion proceeds exponentially, much faster than in the Friedmann regime.

The Einstein equation for flat universe and energy conservation result in the following equations [27]:

$$\begin{aligned}\dot{a}^2(t) &= \frac{8\pi}{3}Ga^2(t)\rho \\ \ddot{a}(t) &= -\frac{4\pi}{3}G(\rho + 3p)a(t) \\ \dot{\rho} &= -3H(p + \rho),\end{aligned}\tag{2}$$

where G is gravitation constant, $a(t)$ is the expansion factor of the metric, $H(t) = \dot{a}/a$ is the Hubble parameter, p and ρ are pressure and density, connected by equation of state $p = p(\rho)$. Let us consider the matter with equation of state $p = -\rho$ and $\rho(t) = \rho_0$, which follows from the third equation above. Such equation of state in particular is realized by scalar field ϕ rolling down in quasi-flat potential. Eqs. (2) are easily solved in this case:

$$a(t) = a_0 e^{H_0 t} \quad \text{with} \quad H_0^2 = \frac{8\pi}{3}G\rho_0,\tag{3}$$

The solution (3) describes exponentially expanding bubble with constant Hubble parameter H_0 . This regime is called inflation.

Inflation obviously solves the horizon problem, because the size of bubble $a(t)$ is much larger at any time t than the size of the observed universe and thus all observed regions are causally connected.

The problem of flatness is also solved. To demonstrate it let us generalize the first equation (2) to the cases of closed ($k = 1$), open ($k = -1$) and flat ($k = 0$) universes.

$$\dot{a}^2(t) - \frac{8\pi}{3}Ga^2(t)\rho = -k.\tag{4}$$

Dividing this equation by a^2 , and using $H = \dot{a}/a$ and $\Omega = \rho/\rho_c$ we obtain

$$\Omega - 1 = \frac{k}{a^2 H^2}.\tag{5}$$

For inflationary solution ($p = -\rho$), $H = H_0$ and $a(t) \sim \exp(H_0 t)$ we see that at the end of inflation, e.g. $t \sim 100H_0^{-1}$ the r.h.s. is negligibly small, providing the flatness at inflation and at all later universe ages up to $t \sim t_0$.

3.1. Where is Dark Matter?

Observational cosmology is characterized now by very precisely determined parameters, and the main contribution to accuracy of their determination is given by WMAP data [28]. WMAP confirms well Λ CDM model with 6 parameters and the main parameters have the following values: $H_0 = 73.2$ km/sMpc, $\Omega_{\text{tot}} = 1 + \Omega_k$, $\Omega_k = -0.011 \pm 0.012$, $\Omega_b = 0.0416$, $\Omega_m = 0.238$, $\Omega_\Lambda = 0.716$. However, the precise determination of cosmological parameters are given by combination of WMAP data with other observations such as SNI, lensing, Large Scale Structures (LSS) and others. The most important results are determination of fraction of Dark Matter (DM) and Dark Energy (DE). We summarize here the status of DM according to these and other observations.

Direct search for DM gives positive result only in observation of modulation signal by DAMA [29]. It does not imply the direct contradiction between DAMA and other experiments: the comparison is always model dependent and difference in target affects the comparison (see [29]).

The strongest evidence for DM is given by *indirect* methods. They include:

- According to WMAP data density of matter Ω_m exceeds much the baryon density Ω_b (see the data above). The presence of DM is seen directly from WMAP data: without DM the height of the third acoustic peak would be much lower than observed.
- Virial (gravitational) mass of galaxies and clusters of galaxies is much larger than baryonic gas: $M_{\text{vir}} \gg M_b$.
- Theory of LSS formation (hierarchical clustering model) successfully explains the LSS formation using dominance of DM.

As was mentioned above only in DAMA the positive direct signal from DM (modulation) is observed. Inspired by negative results in other experiments, some authors develop the alternative theories based on modified gravity. The pioneering works in this direction, Modified Newtonian Dynamics (MOND), have been performed by Milgrom [30]. MOND is characterized by critical acceleration $a_0 \sim 1 \times 10^{-8} \text{ cm s}^{-2}$. At $a < a_0$ the Newtonian mechanics is modified, and the effects of DM are described by modified gravity. The essential step forward in construction of a theoretical model for modified General Relativity (GR) was made in the work by Bekenstein [31]. He has build theoretically correctly the relativistic model of gravitation, TeVeS, introducing three gravitational fields $g_{\mu\nu}$ (tensor, like in GR), U_μ (vector) and ϕ (scalar). Apart from it the model includes a non-dynamical scalar σ , dimensional constants G and l , two dimensionless parameters k and K and one arbitrary function $F(\sigma)$. The model tends to the standard GR in the proper limit and describes effects of MOND at low acceleration. Thus, the model is much more complicated than the standard GR and the only physical motivation of it is given by possibility to avoid DM. This model successfully describes (with baryonic matter only) flat rotation curves in galaxies, high velocities in clusters and lensing. Recent work [32] indicates that TeVeS may provide the perturbation spectrum needed for LSS formation.

There are, however, two contradictions of MOND with observations:

- (i) In the absence of DM the height of the third acoustic peak must be much lower than observed by WMAP. In the paper [28] one can find more general statement: “Models without dark matter are very poor fits to the data”.
- (ii) In the observed “bullet cluster” 1E0657-558 [33] (two colliding clusters) the gravitational potential is not centered by X-ray emitting gas, which is the dominant baryon component in this cluster (the ratio of the masses for gas and galactic components is $M_{\text{gas}}/M_{\text{gal}} \sim 5 - 7$).

In conclusion, I think that there is no DM puzzle. DM particles are not seen in the directly-search experiments, either because sensitivity is still low or because DM particles interact superweakly with ordinary matter (e.g. gravitinos or SHDM particles). MOND and TeVeS should be considered just as interesting alternatives.

3.2. Accelerated expansion of the universe

As follows from the second equation (2) for matter with equation of state $p = \omega\rho$ and with $\omega < -1/3$, acceleration $\ddot{a} > 0$, i.e. we have accelerating expansion of metric. This is generalization of the inflation case $\omega = -1$ which we considered above: $a(t) \propto \exp(H_0 t)$ and $\rho = \rho_0$ (vacuum energy). In the general case there can exist both the matter described by energy-momentum tensor $T_{\mu\nu}$ in the Einstein equation and vacuum energy described by term $\rho_{\text{vac}} g_{\mu\nu}$. The latter is Lambda term, where $\Lambda = 8\pi G \rho_{\text{vac}}$. In the general covariant form the Einstein equation reads

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G (T_{\mu\nu} - \rho_{\text{vac}} g_{\mu\nu}). \quad (6)$$

Presence of Λ term results in acceleration of expansion. While density of ordinary matter in $T_{\mu\nu}$ diminishes with time, ρ_{vac} remains constant, and finally it dominates. Starting from this moment universe enters again the phase of exponential expansion.

The presence of acceleration in the universe is established experimentally in terms of non-zero Λ -term, but more generally the data can be explained also by other terms which cause accelerated expansion. For example, the SN data are explained by non-standard dependence $H(z)$, where H is the Hubble parameter. Such dependence might appear due to matter with equation of state $p = \omega\rho$ and $-1 < \omega < -1/3$. This matter is usually referred to as Dark Energy (DE) fluid.

In principle there are three sources which cause cosmic acceleration:

1. Vacuum energy (Λ -term) in Eq.(6).
2. DE fluid in $T_{\mu\nu}$ with equation of state $p = \omega\rho$ and $\omega < -1/3$. It can be realized as *quintessence*, ultra-light scalar field rolling down the potential; *phantom*, ghost field with equation of state given by $\omega < -1$; *k-essence*; *Chaplygin gas* etc. (for review see [34, 35]).
3. Modified gravity. In this case the modified part of Eq. (6) is its l.h.s. No Λ -term or DE is needed for acceleration and explanation of observational data. The most interesting example is given by DGP [36] extra dimension model, where gravity can leak into the bulk only at large distances. This is one-parameter model which explains the observed acceleration.

Is it possible to distinguish between these possibilities by observations?

Some options differ by spectrum of fluctuations and by equations of state. WMAP data efficiently distinguish the models with different ω . The combined data of WMAP, LSS and SN gives $\omega = -1.08 \pm 0.12$. With a prior assumption of flat universe the above data give $\omega = -0.967 \pm 0.073$. It coincides well with prediction of theory with Λ -term ($\omega = -1$) and is allowed by some other models. Thus, the model with Λ -term ($\rho_{\text{vac}} = \text{const}$) is allowed and preferable by its simplicity.

3.3. Vacuum energy problem

Associated with Λ -term, the vacuum energy density is given numerically as

$$\rho_{\Lambda} = \Lambda/8\pi G = \Omega_{\Lambda}\rho_c = 4 \times 10^{-47} \text{ GeV}^4, \quad (7)$$

for $\Omega_{\Lambda} = 0.73$ [28]. The vacuum energy ρ_{Λ} can be presented as sum of energy density of some cosmological field(s) σ and zero-modes of all known fields (particles) i . Taking them as quantum oscillators with ground-state energy $\omega_k/2$ one obtains vacuum energy of field i

$$\rho_{\text{vac}}^i = \int_0^{k_{\text{max}}^i} \frac{d^3k}{(2\pi)^3} \frac{\omega_k}{2}. \quad (8)$$

Then the total vacuum energy is given by

$$\rho_{\Lambda} = \rho_{\sigma} + \sum_i \rho_{\text{vac}}^i. \quad (9)$$

The problem is that the second term in r.h.s. of Eq. (9) is too large. For example, the reliably known and existing now in the universe quark-gluon condensate has vacuum energy between $-3 \times 10^{-3} \text{ GeV}^4$ as estimated in pioneering work [37] and -0.01 GeV^4 in modern lattice QCD calculations. Its absolute value exceeds the cosmological vacuum energy density (7) by 45 orders of magnitude (for further discussion see [38]).

The problem of too large zero-mode energy of ordinary fields in comparison with cosmological constant is very old. It was already discussed in late sixties (see [39]). It is important to emphasize that this problem consists in cosmologically too large vacuum energy of known fields and thus it is present for example in all DE models. It may be a problem of elementary-particle physics. For example with unbroken supersymmetry there is exact compensation between

negative vacuum energies of bosons and positive of fermions. However, realistic breaking of this symmetry leaves the vacuum energy too large. The 40 years of existing the problem were 40 years of intensive brain attack ... and the problem still exists. Among the proposed solutions there were the beautiful ones. Among the authors there were the stars of theoretical physics such as S. Coleman, S. Hawking, S. Weinberg, E. Witten, Ya. Zeldovich. It makes me think that this puzzle will have some unexpected solution.

S. Weinberg in his review “The cosmological constant problem” [40] describes five roads which could lead to the solution:

1. supersymmetry and supergravity,
2. anthropic approach,
3. adjustment mechanisms,
4. alternative gravity,
5. quantum cosmology.

All approaches are qualified as interesting and promising (quantum gravity especially) but for all of them are indicated the weak points, which do not allow to consider them as the correct, final solution.

As the new direction we can add to the Weinberg list the extra-dimension approach studied recently (for a review see [34]).

3.4. Acceleration and Anthropic approach

- Why Λ -term is zero or very small?
- Why does acceleration start now?
- Why physical parameters are tuned to produce life?

These questions might have answers not in terms of physical principles, but because in a universe with the “wrong” parameters there is nobody to measure them. This is an anthropic solution. For many interesting details I direct a reader to the exiting book of A. Vilenkin “Many Worlds in One” [41].

The answer in the Anthropic approach to the above questions consists in assumption that there is the infinite number of universes where Λ (or ρ_{vac}) takes huge variety of different values. In fact, these quantities do not have the fundamental character to be the universal ones. The matter density ρ_m diminishes with time faster than ρ_{vac} . Then if Λ is small (negative) a universe collapses early and galaxies (observers) are not produced. If Λ is too large the exponential expansion begins early and galaxies are not produced, as well. The galaxy formation occurs roughly when $\rho_{\text{vac}} \sim \rho_m$. This is the basics of answering to the first two questions and relevant calculations one can find in [42], where the value of Λ was predicted.

The third question has a name “coincidences”. To provide the life many physical constants cannot be changed even by very small amount. The famous example is given by F. Hoyle [43]: the resonance in reaction $3He^4 \rightarrow C^{12}$ is the most important channel of carbon production in stars, without it we would not have life (observer). There are many other coincidences, described e.g. in [44].

3.5. From Inflation to Anthropic approach

Anthropic approach very naturally appears in chaotic-inflation scenario [45]. In this scenario the distribution of the inflaton field ϕ in early universe is assumed to be chaotic and respectively the potential $V(\phi)$ is characterized by different values from very low ones up to M_{Pl}^4 . In fact, this postulate of chaotic inflation is very reasonable because different initial domains, separated by distance larger than horizon, must have the different ϕ and V . Inflation is characterized by

$H(\phi) = \text{const}$ for each domain, where ϕ is quasi-homogeneous and it proceeds independently in each horizon domain of size $H^{-1}(\phi)$, which are called mini-universes. At present epoch $t = t_0$ the size of each mini-universe is many orders of magnitude larger than the horizon size $\sim 10^{28}$ cm.

Since value of Λ (ρ_{vac}) is determined by ϕ the different mini-universes are characterized by different values of Λ . It provides a possibility of anthropic selection of Λ .

The chaotic inflation automatically results in the “eternal inflation” [46], a process which has no beginning and end. It occurs because the chaotic inflation includes two competing processes of regeneration of inflationary regions and their decay. There is some critical value ϕ_c below which ϕ oscillate, potential energy is transferred to particles, and the Friedmann expansion begins. On the other hand the region with relatively small ϕ can through quantum tunneling turn into region of much larger size. After tunneling the matter density ρ_m becomes smaller, while ρ_{vac} remains the same. As a result $\rho_{\text{vac}} > \rho_m$ provides the new round of inflation. In Ref.[46] the process of increasing ϕ and ρ_{vac} is described as diffusion of ϕ to higher values as quantum fluctuation process. Thus the Universe always consists of exponentially large number of mini-universities, part of which inflate and part experiences Friedmann expansion. They have the different values of Λ , and therefore some of them might have an observer.

All mini-universes have connected space-time. However, there can be also the large or infinite number of universes with disconnected space-time. This scenario is provided by “creation of a universe from nothing” [47]. A closed universe with zero total energy can be created by quantum tunneling from initial object which has a vanishing size and mass. This object can be considered as “nothing”. If after-tunneling object has the Planck size or less, it immediately collapses, if more - it inflates, producing a disconnected space-time and a universe. All these universes have different mini-universes with different Λ .

3.6. Status of anthropic approach

Anthropic approach to the problem of vacuum energy is different from all other physics solutions and its status will depend on whether or not the irreproachable ordinary-physics solution (e.g. the compensation solution) will be found or not. I will remind again that cosmological constant problem exists for more than 40 years, attracting much attention of physics community. The negative attitude of large part of physics community to the anthropic approach could be conservatism of *present generation*, and some indication of it is given by discussion of anthropic solution by such deep thinkers of our generation as S. Weinberg, S. Hawking, M. Rees, A. Vilenkin, A. Linde and others. It could be that next generation of physicists will consider the anthropic approach as an ordinary physics. In fact, the anthropic approach reminds that of quantum mechanics. The quantum state of a universe with a fixed value of Λ can be described by the wave function [48], which gives the distribution of universes over different values of Λ . In another version of this formalism [49] each universe is characterised not by single value of Λ , but by their superposition, with the wave function giving again a probability to find a universe with fixed value of Λ . The presence of observer in a universe (anthropic selection) plays the role similar to the macro-detector in quantum mechanics.

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